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Long-term residue and water management practice effects on particulate organic matter in a loessial soil in eastern Arkansas, USA

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ABSTRACT

Long-term sustainability of soils with a prolonged history of crop production can be better understood by characterizing soil aggregation, particularly the distribution of carbon (C) and nitrogen (N) among particulate organic matter (POM) fractions within various soil aggregate-size fractions. The objective of this field study was to evaluate the effects of residue level, residue burning, tillage, and irrigation on macro-aggregate (> 250 μm), micro-aggregate (53–250 μm), coarse (> 250 μm) and fine POM (53–250 μm), and silt-clay fractions and their associated C and N in the top 10 cm of a highly erodible loessial soil (Glossaquic Fraglossudalf) after 13 years of consistent management in a wheat-soybean, double-crop (WSDC) system in the Lower Mississippi River Delta region of eastern Arkansas. The total aggregated soil fraction was 11.2% greater ($P = 0.02$) in the no-tillage (NT)-irrigated compared to the average of the other three tillage-irrigation combinations, which did not differ. Averaged over irrigation, burn, and residue-level treatments, the C concentration in the sand-free macro-aggregate fraction was 8.8% less ($P < 0.05$) under conventional tillage (15.6 g kg^{-1}) than under NT (17.1 g kg^{-1}). Fine POM C and N concentrations within sand-free-adjusted aggregates were 1.9 times greater ($P \leq 0.04$) in the burn-low (2.59 and 0.21 g kg^{-1}, respectively) compared to the burn-high treatment (1.35 and 0.11 g kg^{-1}, respectively), while that in the no-burn under either residue level, which did not differ, were intermediate (2.43 and 0.23 g kg^{-1}, respectively). Results showed that alternative management practices, such as NT and non-burning, can contribute to improved soil health and long-term sustainability and the mitigation of climate-change-related greenhouse gas concentrations in the atmosphere by reducing SOM oxidation, microbial respiration, and carbon dioxide emissions.

1. Introduction

Conventional agricultural management practices can degrade soil health (Franzluebbers and Doraiswamy, 2007), particularly due to negative effects on soil aggregation and soil carbon (C) retention. Conventional agricultural management practices, including annual tillage and crop residue burning, can exacerbate the oxidation of soil organic carbon (SOC) via respiration, thus contributing to increased atmospheric greenhouse gas concentrations and increased average global air temperatures (Environmental Protection Agency (EPA), 2016; Intergovernmental Panel on Climate Change (IPCC), 2013; Stevenson, 1986). Depletion of approximately half of the original SOC in undisturbed ecosystems (i.e., forest and grasslands) has been reported in 10 years after conversion to conventional tillage (CT) agriculture (Lal and Bruce, 1999). However, implementation of less-intensive and more sustainable agricultural management practices, such as conservation tillage and other alternative residue management practices, which can also at least maintain or increase food production, can increase soil organic matter (SOM), hence SOC storage (Lal, 2000; Pretty, 2008).

Soil aggregation provides one mechanism of increased SOC storage by physically protecting partially decomposed plant residue (Paul, 2016). Increasing aggregate stability can reduce erosion, increase root growth, and provide additional physical protection of SOM, thereby effectively increasing SOC storage by lowering exposure to oxidation, erosion, and microbial degradation (Wander and Bidart, 2000). Alternative agronomic management practices that increase organic matter inputs and reduce physical soil disturbance, such as conservation tillage practices, including no-tillage (NT) and refraining from residue burning, can increase aggregate stability, thus leading to greater SOC and soil fertility (Cates et al., 2016; Franzluebbers and Doraiswamy,

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2007; Six et al., 2000).Compared to CT, NT has been shown to have consistently greater near-surface SOC (Jagadamma and Lal, 2010; (Yoo and Wander, 2008)) and total particulate orgainc matter (POM) C (Álvaro-Fuentes et al., 2008; Jagadamma and Lal, 2010; Liebig et al., 2004) as a result of less soil disturbance and reduced SOM decomposition under NT than CT. Furthermore, repeated annual CT can promote accelerated physical breakdown of macro- into micro-aggregates, while undisturbed soils enhance macroaggregate stability, as well as the stabilization of micro-aggregates-associated SOM within macroaggregates (Six et al., 2014). However, a multiple regression analysis involving 150 studies demonstrated no difference in total POM C concentration due to tillage treatments (Gosling et al., 2013). Therefore, previous reports are inconclusive regarding the effects of tillage on POM-associated soil properties.

Regardless of management practice, the partial decomposition of fresh plant residues facilitates the formation of POM, which becomes nucleation centers for microbial activity and aggregation (Puget et al., 1995; Six et al., 1999). Microbial activity releases organic polymers that binds the partially processed residue with sediments to result in soil macro-aggregate (> 250 μm) formation. Soil macro-aggregates subsequently breakdown into smaller particles to form micro-aggregates (53–250 μm; (Six et al., 2004)), while the < 53-μm fraction is generally considered the non-aggregated, mineral fraction. Balesdent et al. (2000) showed that the protection of POM-derived SOC generally increases with greater SOM and clay, but is reduced by frequent tillage (Cates et al., 2016). Consequently, agronomic management practices that impact the amount of residue returned to the soil, such as CT, residue burning, nitrogen (N) fertilization, and irrigation, can greatly affect soil aggregation and aggregate stability by impacting POM formation (Balesdent et al., 2000).

Optimal N fertilization, residue burning, CT, and furrow irrigation are the traditional set of conventional management practices associated with the wheat (*Triticum aestivum* L.)-soybean (*Glycine* max [L.] Merr.), double-crop (WSDC) production system in the mid-southern United States, particularly in the Lower Mississippi River Delta (LMRD) region of eastern Arkansas (United States Department of Agriculture (USDA) and National Agricultural Statistics Service (NASS), 2017). Increased above- and belowground plant biomass production and excretion of root exudates associated with optimal N fertilization of the wheat crop in the WSDC system can increase POM (Banger et al., 2010; Malhi and Gill, 2002). Increased mean weight diameter of soil aggregates, which increases protection of POM and SOC, has been reported with inorganic fertilizer and manure applications (Banger et al., 2009). However, a meta-analysis involving differing soil textures, crops, and management variables showed no difference in POM with N fertilization (Gosling et al., 2013). Thus, similar to tillage, previous reports are inconclusive regarding the effects of N fertilization on POM.

Residue burning and CT have been shown to substantially decrease SOM in the LMRD region of eastern Arkansas compared to soils under forage, turfgrass, and/or undisturbed native prairie (Brye and Pirani, 2005; Delong et al., 2003). Residue burning has been shown to remove up to 90% of the aboveground dry matter and C in a WSDC system (Brye, 2012). As a result, only approximately 10% of the aboveground dry matter and C is returned to the soil surface to potentially contribute to POM formation and SOC occlusion in soil aggregates. Sanford (1982) reported decreased SOM and total organic C content due to residue burning in a WSDC system after four years of management in a silty clay (Aquic Chromudert). In contrast, Rasmussen and Parton (1994) suggested the effect of annual residue burning would take 20 to 30 years to impact SOM and crop yield.

Unlike residue burning and CT that generally have negative effects on SOM and SOC compared to the alternative practices of non-burning and NT, irrigation can have variable effects on SOM and SOC compared to the alternative of dryland crop production. Frequent optimal soil moisture conditions provided by irrigation can increase plant productivity, hence the amount of above- and belowground OM that can be returned to the soil to contribute to greater SOM and POM production. Furthermore, frequent optimal soil moisture can increase microbial biomass, subsequently increasing SOC and macro-aggregate formation (Blanco-Canqui et al., 2010), even in fine-textured soils in Arkansas (Jacobs et al., 2015). In contrast, optimal soil moisture can potentially decrease POM by increasing microbial activity and the decomposition of SOM (Churchman and Tate, 1986), thus decreasing SOC storage. In addition, excess surface water, often at least temporarily associated with furrow irrigation of many row crops in the mid-southern United States, can induce physical disruption of unstable aggregates due to slaking (Six et al., 2000). Though the benefits of practices like N fertilization and irrigation can be realized relatively quickly (i.e., within or after one growing season), POM formation and soil aggregation generally occur at slower temporal scales than just a few months. As a result, multiple years are often required for measurable differences between management practices to manifest, as document by differences in mean residence time (Paul, 2016). Thus, long-term field studies (i.e., > 10 years of consistent management), particularly on highly erodible soils to accentuate the benefits of soil aggregation and SOC storage, offer a unique opportunity and are necessary to evaluate POM formation, SOC storage, and soil aggregation, as these processes require more than a few years to manifest management differences (Cates et al., 2016). Furthermore, SOC change over decades, as a result of various agricultural management practices, may be closely tied to the relationship between macro- and micro-aggregation and POM and their associated C and N (Ontl et al., 2015; Six et al., 2014).

No long-term studies exist that have examined the effects of multiple combinations of conventional and alternative agricultural practices for more than a decade on POM in the mid-southern United States. Therefore, the objective of this field study was to evaluate the effects of alternative (i.e., minimal N fertilization producing a low-wheat-residue level, residue non-burning, NT, and dryland soybean production) and traditional (i.e., optimal N fertilization producing a high-wheat-residue level, residue burning, CT, and irrigated soybean production) agronomic practice combinations following 13 years of consistent management on aggregate- and POM-fraction-associated C and N within macro- and micro-aggregates in a long-term WSDC system on a loessial sol in the LMRD region of eastern Arkansas. Conventional tillage and residue burning were hypothesized to reduce overall soil aggregation, POM, and aggregate- and POM-associated C and N compared to NT and non-burning. These hypotheses were based on expected increased mechanical breakdown of soil aggregates and chemical oxidation of SOM under CT and reduced residue amounts returned to the soil as a result of burning ((Balesdent et al., 2000); Wuest et al., 2005; (Brye, 2012; Cates et al., 2016)). Irrigation was hypothesized to have greater soil aggregation, POM, and aggregate- and POM-associated C and N due to greater above- and belowground plant biomass production compared to dryland production (Amuri et al., 2008; Smith et al., 2014b).

2. Materials and methods

2.1. Site description

The WSDC system evaluated in this study was established in 2001 on a Calloway silt-loam (fine-silty, mixed, active, thermic Glossaquic Fraglossudalf; (Brye et al., 2006b; Natural Resources Conservation Service (NRCS) and Soil Survey Staff (SSS), 2017)) with 16% sand, 73% silt, and 11% clay in the top 10 cm (Brye et al., 2006a). The site is located near Marianna in east-central Arkansas at the University of Arkansas – Division of Agriculture's Lon Mann Cotton Research Station (34°, 44′, 2.26″ N lat; 90°, 45′, 51.56″ W long; (Cordell et al., 2006)) in the Southern Mississippi Alluvium [Major Land Resource Area (MLRA) 131A; (Natural Resources Conservation Service (NRCS), 2006)].

The 30-yr (1981 to 2010) mean annual air temperature, mean monthly minimum, and mean monthly maximum in the region are 16.5 °C, 4.2 °C in January, and 27.5 °C in July, respectively (National

Oceanic and Atmospheric Administration (NOAA), 2017a). The 30-yr mean annual precipitation in the region is 128 cm (National Oceanic and Atmospheric Administration (NOAA), 2017b).

2.2. Experimental design and treatments

The original experimental design included three treatment factors [i.e., high- and low-wheat residue level achieved with differential N fertilization, wheat residue burning and no burning, and CT and NT] configured in a three-factor, split-strip-plot design with six replications of eight treatment combinations (Cordell et al., 2006; Desrochers, 2017). Tillage treatment was replicated three times and was stripped across burn treatments. Each tillage-burn combination contained the residue-level treatments as a split-plot factor. In 2005, the study area was divided in half to establish two irrigated and two non-irrigated blocks (Verkler et al., 2009). However, due to logistical field management constraints, irrigation treatment blocks had to be superimposed on the burn treatment blocks, thus rendering the burn and irrigation factors unable to be simultaneously statistically evaluated (Smith et al., 2014a). Consequently, there were a total of 48, 3-m-wide x 6-m-long plots consisting of six replications of each tillage-irrigation/burning-residue-level combinations (Amuri et al., 2008).

2.3. Field management

Prior to establishing this WSDC system in 2001, the field site had been managed in a mono-cropped soybean system with CT (Cordell et al., 2006). In Fall 2001, the study area was disked twice followed by broadcast application of N, P, K, and pelletized limestone to adjust soil fertility for winter wheat production (Cordell et al., 2006). Each year in early to mid-November, wheat was drill-seeded at a rate of 90 kg seed ha^{-1} with 19-cm row spacing. All 48 plots were broadcast-fertilized by hand with urea (46% N) at a rate of 101 kg N ha^{-1} in late March from 2002 to 2004. In 2005, fertilizer application did not occur, as prolonged wet-soil conditions led to failed wheat-stand establishment in 2004. From 2006 onward, high- and low-residue levels were achieved by applying a split application of 101 kg N ha^{-1} in late February and March in the high-residue plots only, with the low-residue plots receiving no fertilizer N.

Each year, in May to early June, wheat was harvested with a plot combine. Subsequently, wheat residue from each plot was uniformly manually raked back on the plot from which it came. Wheat stubble was cut to a height of ≤10 cm with a rotary mower. Following mowing, the burn treatment was imposed in half the plots via propane flaming. The pre-soybean-planting CT treatment followed the common regional practice of disking at least twice with a tandem disk to a depth of 7 to 10 cm followed by use of a soil conditioner to smooth the seedbed. All field implements used were pulled behind an intermediate-sized tractor when the soil moisture content could adequately support the field machinery.

Approximately mid-June from 2002 to 2013, a glyphosate-resistant soybean (maturity group 5.3 or 5.4) was drill-seeded with 19-cm row spacing at a rate of 47 kg seed ha^{-1}. From 2014 and on, an enhanced glyphosate-resistant soybean cultivar (Liberty Link, maturity group 4.9) was drill-seeded at a rate of 101 kg seed ha^{-1}. Potassium fertilizer was applied as needed following recommended rates (University of Arkansas Cooperative Extension Service (UACES), 2000). During the soybean growing season, from 2005 onward, a levee was created to exclude irrigation water from the non-irrigated treatment plots, while the remaining half of the plots received furrow-irrigation three to four times each year. On an as-needed basis, herbicide and insecticide were applied during the wheat and soybean growing seasons for annual weed and insect management (University of Arkansas Cooperative Extension Service (UACES), 2000). In late October to early November, soybean harvest using a plot combine occurred, after which the subsequent wheat crop was sown without any other field manipulations, marking the beginning the subsequent cropping cycle.

2.4. Residue and soil sampling

Following wheat harvest and residue mowing, in 2015, above-ground residue was collected within a 0.25-m^2 frame, oven-dried at 55 °C for seven days, and weighed. At the same time, one soil core from the top 10 cm in each plot was collected using a 4.8-cm diameter stainless steel core chamber and slide hammer and subsequently dried for 48 h at 70 °C and weighed to determine soil pH, which was measured potentiometrically on sub-samples in a 1:2 soil mass:water volume paste. On August 20, 2015, one soil core from the top 10 cm in each plot was collected using a 4.8-cm diameter stainless steel core chamber and slide hammer and subsequently dried for 48 h at 70 °C and weighed to determine bulk density. On September 15, 2015, approximately 15 weeks following soybean planting in order to reduce temporal variability from the most recent imposed treatments (Marschner et al., 2011), 12 to 15, 2-cm diameter soil cores were randomly collected using a push probe from the top 10 cm in each plot and combined for one sample per plot. Samples were stored field moist at room temperature (~21 °C) for several weeks, then air-dried for several weeks prior to being hand-crushed to pass through an 8-mm sieve. Each composite soil sample was used to assess long-term management practice effects on aggregate and POM fractions and associated C and N

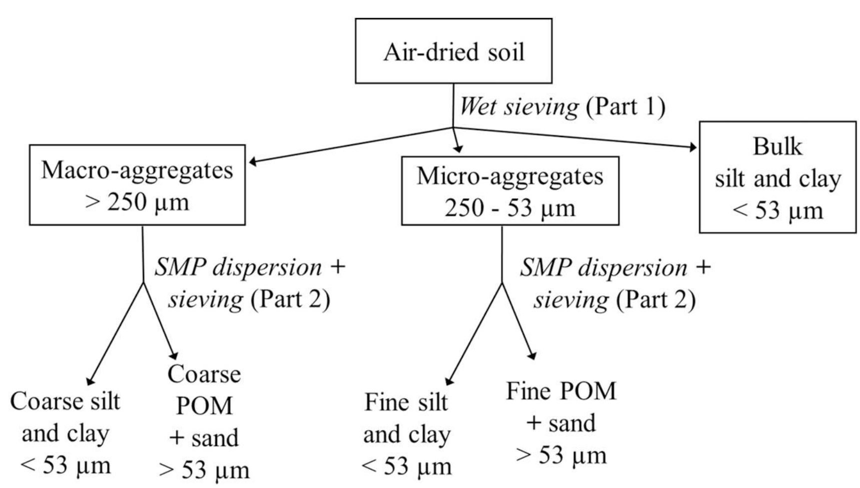

Fig. 1. Flow chart of the aggregate fractionation (Part 1) procedure to obtain macro-aggregates, micro-aggregates, and silt-clay fractions and particulate organic matter (POM) separation (Part 2) procedure to obtain coarse and fine POM.

concentrations according to a procedure similar to Six et al. (1998) (Fig. 1) and further detailed in Desrochers (2017).

2.5. Aggregate fractionation and analyses

An aggregate-size separation method, adapted from Six et al. (1998), was used to fractionate macro- and micro-aggregates. After several weeks of air-drying, soil samples were lightly hand-crushed to pass through an 8-mm sieve. A 95-g subsample was submerged by approximately 1 cm in deionized (DI) water atop a 250-μm mesh sieve resting in a shallow plastic basin for 5 min to induce slaking. The sieve and soil were then submerged in and out of water by oscillating 50 times for 2 min at a 3-cm amplitude, after which the > 250 μm aggregates (i.e., macro-aggregate fraction) retained atop the sieve were transferred by light washing with DI water to a pre-weighed aluminum pan. After allowing macro-aggregates to settle, large floating organic material (> 2000 μm), not considered SOM (Six et al., 1998), was decanted from the metal pan prior to drying. Soil remaining in the plastic basin that passed through the 250-μm sieve was transferred atop a 53-μm mesh sieve within a shallow plastic basin, after which the sieving procedure was repeated to obtain the 53- to 250-μm aggregates (i.e., micro-aggregate fraction). After 24 h of soaking and slaking, the water atop the second plastic basin was decanted and the silt and clay sediments that had settled out of suspension (i.e., silt-clay fraction) were transferred to a pre-weighed metal pan. All size fractions (i.e., macro- and micro-aggregates and silt-clay) were subsequently dried for 24 h at 105 °C (J. Six, personal communication, 2017) in a forced-air oven, allowed to cool in a desiccator, weighed, and stored in glass jars for C and N analyses.

2.6. Particulate organic matter separation and analyses

Similar to aggregate fractionation, a POM separation procedure, adapted from Six et al. (1998), was used to obtain coarse (i.e., macro-aggregate derived) and fine (i.e., micro-aggregate derived) POM. Two, approximately 5-g macro-aggregate-fraction sub-samples were dispersed on a reciprocal shaker for 18 h in 30 mL of 0.5% sodium hexametaphosphate. Dispersed macro-aggregates were then poured over a 53-μm mesh sieve, rinsed with DI water, transferred to a glass beaker, dried for 24 h at 105 °C in a forced-air oven, allowed to cool in a desiccator, weighed, and stored in glass jars for C and N analyses. The same POM separation procedure was performed for the micro-aggregate fraction. The C and N macro- and micro-aggregate as well as coarse- and fine-POM concentrations were reported per sand-free aggregate in order to account for textural differences among size classes, as sand content has little to no effect on organic matter binding (Elliott et al., 1991). Consequently, since both the POM and sand fractions were retained on the sieve and the POM mass was miniscule compared to the sand mass, the sand-sized fraction was assumed to equal the mass of the POM fraction within respective aggregate fractions and calculated using Eq. (1) ((Garland et al., 2016; Six et al., 1998); J. Six, personal communication, 2017):

$$\text{Sand free}(\text{C or N})_{\text{fraction}} = \frac{(\text{C or N})_{\text{fraction}}}{1 - (\text{sand proportion})_{\text{fraction}}} \tag{1}$$

Due to the small sample size, the aggregate size and POM fractions were homogenized by grinding/mixing for 20 s using a Wig-L Bug® (Model MSD, DENTSPLY, York, PA, USA). Using an elemental analyzer (Model NC2500, Carlo Erba, Milan, Italy), C and N concentrations were measured on the bulk-soil, macro- and micro-aggregates, and coarse and fine POM. Based on the product of measured C and N concentrations (mg kg^{-1}), field-measured soil bulk densities on a plot-by-plot basis from August 2015, and the 10-cm sample depth interval, C and N contents (g m^{-2}) were also calculated for data analyses and reporting. The coarse and fine silt-clay fractions were calculated by subtracting POM fraction subsample masses from the total macro- and micro-aggregate subsample masses, respectively (Fig. 1). The bulk silt-clay fraction was calculated by subtracting both coarse- and fine-POM subsample fractions and therefore includes whole-soil silt-clay following aggregate fractionation as well as macro- and micro-aggregate silt-clay following POM separation. The bulk-, coarse- and fine silt-clay associated C and N contents were calculated by difference using macro- and micro-aggregate as well as coarse- and fine-POM C and N contents (g m^{-2} soil) in the following equations ((Six et al., 1999); J. Six, personal communication, 2017):

$$\text{Macro} - \text{aggregate–coarse POM} = \text{coarse} - \text{associated silt} - \text{clay} \tag{2}$$

$$\text{Micro} - \text{aggregate–fine POM} = \text{fine} - \text{associated silt} - \text{clay} \tag{3}$$

$$\text{Bulk} - \text{soil–(coarse POM} + \text{fine POM)} = \text{bulk} - \text{soil} - \text{associated silt} - \text{clay} \tag{4}$$

2.7. Statistical analyses

Since the irrigation block directly corresponded to the burn block, simultaneous statistical analyses including both irrigation and burn treatments were not able to be conducted. Consequentially, data were analyzed using two separate, three-factor analyses of variance (ANOVAs) using PROC MIXED using SAS (version 9.4, SAS Institute, INC., Cary, NC) to evaluate the effects of tillage, burning, residue level, and their interactions as well as tillage, irrigation, residue level, and their interactions on bulk density; micro- and macro-aggregate, and silt-clay soil fractions; bulk-soil, macro- and micro-aggregate, coarse and fine POM, and bulk-soil-, coarse-, and fine-associated silt-clay C and N, and C:N ratios. The PROC MIXED maximum likelihood procedure was used for variables in which the least squared means were not achievable. When appropriate, means were separated using least significant differences (LSD) at the α = 0.05 level.

3. Results

3.1. Residue-level differences and soil bulk density and C and N contents

In 2015, following 13 years of consistent management, post-harvest wheat residue was 1.6 times greater ($P \le 0.03$; Table 1) in the high- (6836 kg ha^{-1}) than the low-residue level treatment (4379 kg ha^{-1}). Furthermore, the cumulative effects of long-term management following conversion from mono-cropped soybean affected soil pH, bulk density, and C and N contents in the top 10 cm. Averaged across irrigation treatments, soil pH was 4.7% lower (pH = 6.4; $P = 0.04$; Table 1) in the NT-burn-high-residue-level combination compared to the average of the other tillage-burn-residue-level treatment combinations, which did not differ and averaged 6.7. Averaged across tillage, burn, and residue-level treatments, soil pH was also 14.5% greater ($P < 0.01$; Table 1) under irrigated (pH = 7.1) compared to non-irrigated conditions (pH = 6.2) due to the slightly alkaline pH of the groundwater used for irrigation. Averaged over irrigation and residue-level treatments, soil bulk density was 7% lower ($P = 0.02$; Table 1) in the NT-no-burn (1.22 g cm^{-3}) compared to the other tillage-burn combinations, which did not differ and averaged 1.31 g cm^{-3}, while bulk density was unaffected by irrigation or residue-level treatments. In contrast to bulk density, averaged over tillage, burn, and residue-level treatments, bulk-soil C and N contents were 18.1 and 11.5% greater ($P = 0.01$; Table 1) under irrigated (1669 and 155 g m^{-2}, respectively) than under non-irrigated conditions (1413 and 139 g m^{-2}, respectively), while bulk-soil C and N contents were unaffected by tillage, burn, and residue-level treatments.

Based on measurements conducted in 2015 alone, after > 13 years of consistent management, the cumulative effects of the various combinations of field treatments evaluated in this study showed little difference in soil C and N storage in the top 10 cm among field treatment

Table 1

Analysis of variance (ANOVA) summary of the effects of tillage, residue level, burning, irrigation, and their interactions on wheat residue, soil pH, soil bulk density, bulk-soil C and N contents (g m^{-2} soil), macro- and micro-aggregate fractions, and silt-clay fractions in the top 10 cm following > 13 years of consistent management in a wheat-soybean, double-crop production system at the University of Arkansas' Lon Mann Cotton Research Station near Marianna, AR on a silt-loam soil.

Source of variation	Wheat residue	pH	Bulk density	Bulk-soil C	Bulk-soil N	Macro-aggregate	Micro-aggregate	Silt-clay
	P							
Tillage (T)[a]	0.86	0.06	< 0.01	0.72	0.62	0.03	0.03	0.13
Residue level (RL)	0.01	0.04	0.90	0.66	0.51	0.81	0.45	0.15
Burn (B)	0.26	0.03	0.04	0.69	0.77	0.05	0.16	0.25
T × RL	0.29	0.42	0.24	0.44	0.91	0.05	0.13	0.06
T × B	0.43	0.77	0.02	0.50	0.57	0.15	0.20	0.83
B × RL	0.83	0.17	0.96	0.34	0.25	0.65	0.50	0.02
T × B × RL	0.32	0.04	0.27	0.08	0.44	0.60	0.72	0.40

Source of variation	Wheat residue	pH	Bulk density	Bulk-soil C	Bulk-soil N	Macro-aggregate	Micro-aggregate	Silt-clay
	P							
Tillage[a]	0.80	0.07	0.01	0.59	0.60	0.03	0.03	0.13
Residue level	0.03	0.06	0.91	0.71	0.46	0.81	0.36	0.02
Irrigation (I)	0.62	< 0.01	0.67	0.01	< 0.01	0.31	0.25	0.77
T × RL	0.17	0.44	0.14	0.36	0.90	0.01	0.04	0.11
T × I	0.73	0.35	0.37	0.83	0.45	0.47	0.74	< 0.01
I × RL	0.03	0.25	0.16	0.82	0.21	0.48	0.24	< 0.01
T × I × RL	0.50	0.38	0.21	0.22	0.63	0.32	0.26	0.90

[a] Two sets of three-factor ANOVAs were conducted due to the similar blocking structure for the burn and irrigation treatments.

combinations, with the exception of greater C and N contents under irrigated compared to dryland soybean production. However, these results underscore the complexity of potential interactions that can affect soil C and N cycling and dynamics (Paul, 2016) in the SOM-rich A horizon. Consequently, a deeper examination was necessary to ascertain whether more than a decade of CT versus NT or residue burning versus non-burning management indeed had little cumulative effects or whether more subtle differences in soil aggregation and POM had developed at a smaller scale that were not manifested yet at the bulk-soil scale.

3.2. Aggregate size fractions and associated C and N

Averaged over irrigation treatments, the soil macro-aggregate fraction in the top 10 cm ranged from 50.3 to 67.1% in the NT-burn-low- and CT-no-burn-high-residue combinations, respectively, while the micro-aggregate fraction ranged from 19.5 to 34.5% in the CT-non-burn-high- and NT-burn-high-residue combinations, respectively. The non-structured silt-clay fraction ranged from 13.5 to 16.3% in the CT-no-burn-high- and CT-burn-low-residue combinations, respectively.

As was expected, the soil macro- and micro-aggregate fractions differed among several field treatments following > 13 years of consistent management. Averaged across irrigation, tillage, and residue-level treatments, the macro-aggregate fraction was 1.1 times greater ($P < 0.05$; Table 1) under the no-burn (62.2%) compared to the burn treatment (58.0%). In addition, but contrary to that hypothesized, averaged across irrigation and burn treatments, the macro-aggregate fraction was greater ($P < 0.05$; Table 1) under CT in both the high- and low-residue treatments (65.8 and 63.1%, respectively), which did not differ, compared to the high- and low-residue treatments under NT (54.1 and 57.4%, respectively), which also did not differ (Fig. 2). Averaged across irrigation and burn treatments, the micro-aggregate fraction was 1.1 times greater ($P = 0.04$; Table 1) in the high- compared to low-residue treatment under NT (31.0 and 27.4%, respectively), while the NT-high-residue level combination was 1.5 greater than in both residue-level treatments under CT, which did not differ and averaged 21% (Fig. 2). Neither the macro- nor micro-aggregate fractions in the top 10 cm were affected by irrigation.

In contrast to the aggregated fractions, the non-aggregated silt-clay fraction was affected by all four field treatments evaluated (Table 1). Averaged across irrigation and tillage treatments, the silt-clay fraction was 11.2% greater ($P = 0.02$) in the burn-low-residue (16.0%) compared to the other three burn-residue-level combinations, which did not differ and averaged 14.4% (Fig. 3). Averaged across tillage and burn treatments, the silt-clay fraction was 1.15 times greater ($P < 0.01$) under the irrigated-low- (15.6%) compared to the irrigated-high-

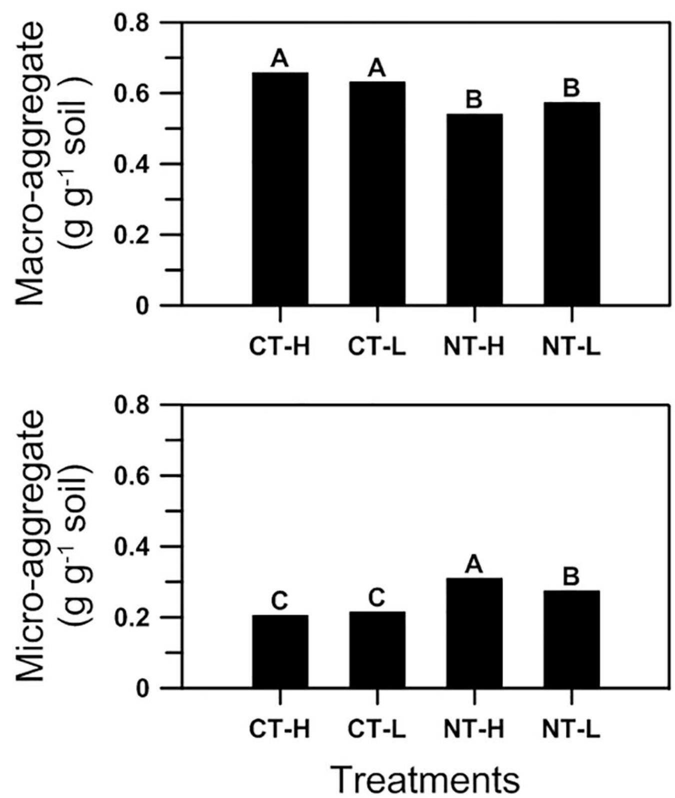

Fig. 2. Tillage [conventional tillage (CT) and no-tillage (NT)]-residue-level [high (H) and low (L)] treatment effects on macro- (top) and micro-aggregate soil concentrations in the top 10 cm of soil in September 2015 following more than13 years of consistent management in a wheat-soybean, double-crop system near Marianna, AR. Different letters atop bars within a panel denote significant differences between treatment combinations.

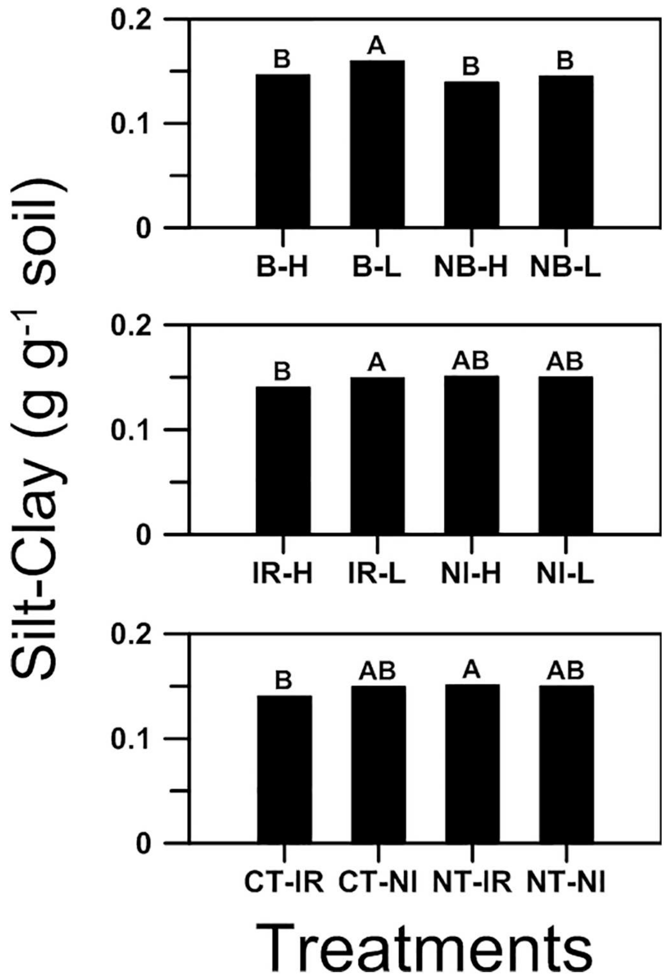

Fig. 3. Burn [burn (B) and no-burn (NB)]-residue-level [high (H) and low (L)] (top), irrigation [irrigated (IR) and non-irrigated (NI)]-residue-level (middle), and tillage [conventional tillage (CT) and no-tillage (NT)]-irrigation treatment effects on silt-clay-associated soil concentrations in the top 10 cm of soil in September 2015 following > 13 years of consistent management in a wheat-soybean, double-crop system near Marianna, AR. Different letters atop bars within a panel denote significant differences between treatment combinations.

residue-level combination (13.6%), while the non-irrigated-residue level combinations were intermediate and averaged 15% (Fig. 3). Averaged across burn and residue-level treatments, the silt-clay fraction was 1.1 times greater ($P < 0.01$) under NT (15.1%) compared to CT (14.1%) under irrigated conditions, while the non-irrigated-tillage combinations were intermediate and did not differ (Fig. 3).

Adjusted to a sand-free-aggregate concentration, aggregate-associated C and N were affected by few field treatments (Table 2). Averaged over irrigation, burn, and residue-level treatments, the sand-free macro-aggregate C concentration was 8.8% less ($P < 0.05$) under CT (15.6 g kg^{-1}) than under NT (17.1 g kg^{-1}). Sand-free macro-aggregate N concentration and C:N ratio and micro-aggregate C and N concentrations and C:N ratio were unaffected by any field treatments evaluated in this study (Table 2).

In contrast to C and N concentrations, sand-free micro-aggregate C and N contents in the top 10 cm were affected ($P < 0.05$) by several field treatments. Averaged across irrigation and burn treatments, the micro-aggregate C content was 64 and 27% greater ($P < 0.01$) in the NT-high- (413 g m^{-2}) and NT-low-residue combination (319 g m^{-2}) compared to the high- and low-residue combinations under CT (255 and 248 g m^{-2}, respectively), while that in the NT-high- was also 29% greater than in the NT-low-residue combination (Fig. 4). In addition, averaged across irrigation and burn treatments, the micro-aggregate N content was 55 and 23% greater ($P < 0.01$) in the NT-high- (41.87 g m^{-2}) and NT-low-residue combination (33.2 g m^{-2}) compared to the high- and low-residue combinations under CT (26.2 and 27.7 g m^{-2}, respectively), while that in the NT-high- was 26% greater than in the NT-low-residue combination (Fig. 4). Similarly, averaged across irrigation and residue-level treatments, micro-aggregate C and N contents were 1.6 ($P = 0.02$) and 1.5 ($P = 0.05$) times greater under the NT (399 and 39.4 g m^{-2}, respectively) compared to under CT (248 and 27.2 g m^{-2}, respectively) when residue was burned, while micro-aggregate C and N contents were 1.4 and 1.3 times greater under the NT (333 and 33.2 g m^{-2}, respectively) compared to under CT (256 and 26.7 g m^{-2}, respectively; Fig. 5) when residue was left unburned. In contrast to sand-free micro-aggregate C and N contents, neither macro-aggregate nor silt-clay fraction C and N contents were affected ($P > 0.05$) by any field treatments evaluated in this study and averaged 1127 g C m^{-2}, 108 g N m^{-2}, 1039 g C m^{-2}, and 110 g N m^{-2}, respectively, across all treatments after 13 years of consistent management (Figs. 4 and 5).

3.3. C and N in particulate organic matter fractions

Fine (i.e., 53–250 µm) POM C and N concentrations in the top 10 cm, adjusted to a sand-free basis, differed ($P < 0.05$; Table 2) between residue levels within burn treatments. Averaged across irrigation and tillage treatments, fine POM C and N concentrations were 1.9 times greater in the burn-low- (2.6 and 0.2 g kg^{-1}, respectively) than in the burn-high- (1.3 and 0.1 g kg^{-1}, respectively), whereas fine POM C and N concentrations in the no-burn-high- (2.6 and 0.2 g kg^{-1}, respectively) and no-burn-low-residue combinations (2.43 and 0.23 g kg^{-1}, respectively) were intermediate and did not differ (Fig. 6). In contrast, coarse (i.e., > 250 µm) POM C concentration was unaffected ($P > 0.05$) by any field treatments and averaged 6.9 and 0.5 g kg^{-1}, respectively (Fig. 6). Although ANOVA determined coarse POM N concentration to differ ($P < 0.01$) between residue levels within irrigation treatments (Table 2), treatment combination means were unable to be separated based on the LSD approach used. On a concentration basis, averaged across burn, tillage, and residue-level treatments, fine POM C:N ratio was 16% greater ($P < 0.01$; Table 2) under non-irrigated (13.7) compared to irrigated conditions (11.9). In contrast, coarse POM C:N ratio was unaffected ($P > 0.05$) by any field treatment evaluated in this study and averaged 13.7 across all treatment combinations.

Similar to concentration results, coarse POM C content in the top 10 cm was unaffected ($P > 0.05$) by any field treatment (Table 3) and averaged 441 g m^{-2} across all treatment combinations. However, in contrast, coarse POM N and fine POM C and N contents were affected by several field treatments ($P < 0.05$; Table 3). Averaged across irrigation, tillage, and residue-level treatments, coarse POM N content was 15.1% greater ($P = 0.04$) in the no-burn (34.3 g m^{-2}) compared to the burn treatment (29.8 g m^{-2}). Furthermore, averaged across tillage and burn treatments, coarse POM N content was 21.0% greater ($P = 0.03$) in the irrigated-low- (42.7 g m^{-2}) compared to the irrigated-high-residue combination (35.3 g m^{-2}), whereas the coarse POM N content in the low- and high-residue levels under irrigation were 68.1 and 39.0% greater than that in the respective non-irrigated treatments, which did not differ and averaged 25.4 g m^{-2} (Fig. 7). However, averaged across irrigation, tillage, and burn treatments, fine POM C and N contents were 1.2 ($P = 0.05$) and 1.3 ($P = 0.04$) times greater under the low- (69.8 and 5.6 g m^{-2}, respectively) compared to the high-residue treatment (57.1 and 4.3 g m^{-2}, respectively).

3.4. Silt-clay fraction C and N

After > 13 years of consistent management, coarse-associated silt-clay C and fine-associated silt-clay C and N contents in the top 10 cm were affected ($P < 0.05$) by several field treatments (Table 3). Though

Table 2
Analysis of variance (ANOVA) summary of the effects of tillage, residue level, burning, irrigation, and their interactions on macro- and micro-aggregate, coarse and fine particulate organic matter (POM) carbon (C) and nitrogen (N) concentrations (g kg^{-1} sand-free aggregate) and their C:N ratios in the top 10 cm following > 13 years of consistent management in a wheat-soybean, double-crop production system at the University of Arkansas' Lon Mann Cotton Research Station near Marianna, AR on a silt-loam soil.

Source of variation	Macro- C	Macro- N	Macro- C:N	Micro- C	Micro-N	Micro-C:N	Coarse POM C	Coarse POM N	Coarse POM C:N	Fine POM C	Fine POM N	Fine POM C:N
	P											
Tillage (T)[a]	0.05	0.13	0.92	0.12	0.48	0.12	0.19	0.12	0.77	0.35	0.34	0.62
Residue level (RL)	0.57	0.59	0.72	0.38	0.64	0.07	0.94	0.61	0.22	0.03	0.07	0.37
Burn (B)	0.31	0.36	0.72	0.68	0.47	0.22	0.83	0.63	0.29	0.63	0.60	0.43
T × RL	0.75	0.27	0.88	0.71	0.29	0.34	0.58	0.95	0.56	0.91	0.76	0.33
T × B	0.49	0.65	0.13	0.92	0.73	0.55	0.14	0.30	0.16	0.96	0.45	0.09
B × RL	0.06	0.42	0.06	0.68	0.28	0.74	0.35	0.75	0.14	0.04	0.02	0.75
T × B × RL	0.40	0.47	0.89	0.86	0.92	0.56	0.79	0.42	0.22	0.52	0.31	0.34

Source of variation	Macro- C	Macro- N	Macro- C:N	Micro- C	Micro-N	Micro-C:N	Coarse POM C	Coarse POM N	Coarse POM C:N	Fine POM C	Fine POM N	Fine POM C:N
	P											
Tillage[a]	0.13	0.13	0.75	0.12	0.48	0.12	0.32	0.23	0.75	0.35	0.34	0.63
Residue level	0.63	0.45	0.24	0.26	0.50	0.21	0.98	0.67	0.24	0.02	0.01	0.30
Irrigation (I)	0.44	0.43	0.60	0.22	0.41	0.59	0.09	0.19	0.60	0.31	0.28	< 0.01
T × RL	0.85	0.63	0.50	0.76	0.40	0.18	0.75	0.98	0.50	0.87	0.72	0.30
T × I	0.91	0.62	0.37	0.87	0.39	0.37	0.85	0.65	0.37	0.20	0.19	0.32
I × RL	0.09	0.19	0.19	0.08	0.10	0.32	0.13	< 0.01	0.19	0.72	0.82	0.74
T × I × RL	0.51	0.82	0.64	0.72	0.61	0.21	0.66	0.69	0.64	0.55	0.77	0.26

[a] Two sets of three-factor ANOVAs were conducted due to the similar blocking structure for the burn and irrigation treatments.

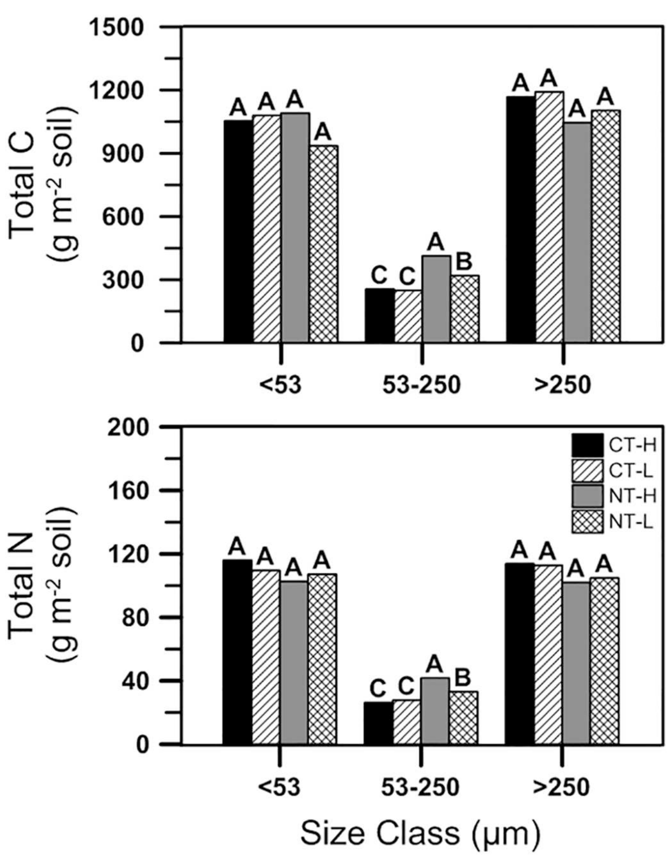

Fig. 4. Tillage [conventional tillage (CT) and no-tillage (NT)]-residue-level [high (H) and low (L)] treatment effects on total C (top) and N (bottom) contents among aggregate-size classes in the top 10 cm of soil in September 2015 following > 13 years of consistent management in a wheat-soybean, double-crop system near Marianna, AR. Different letters atop bars within a size class within a panel denote significant differences between treatment combinations.

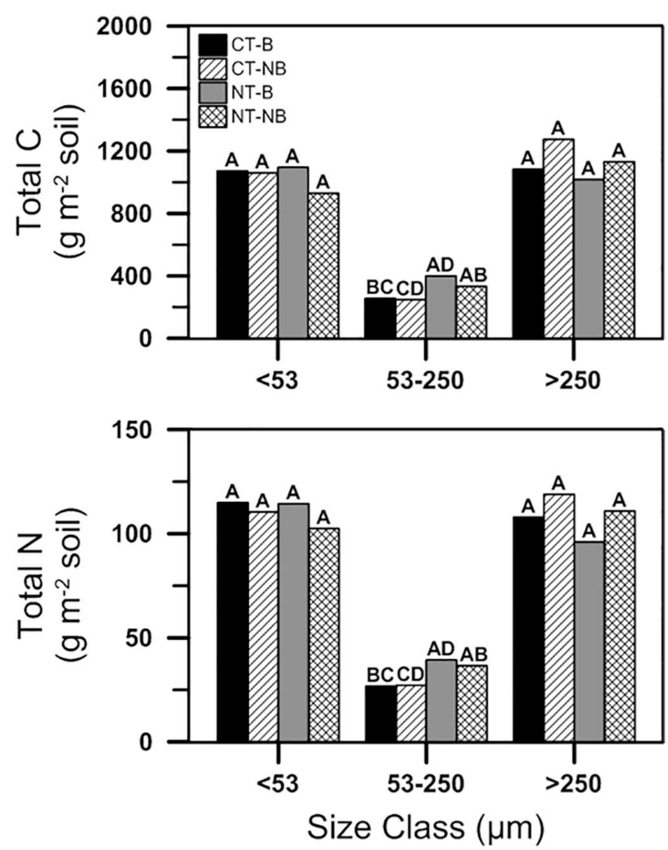

Fig. 5. Tillage [conventional tillage (CT) and no-tillage (NT)]-burn [burn (B) and no burn (NB)] treatment effects on total C (top) and N (bottom) contents among aggregate-size classes in the top 10 cm of soil in September 2015 following > 13 years of consistent management in a wheat-soybean, double-crop system near Marianna, AR. Different letters atop bars within a size class within a panel denote significant differences between treatment combinations.

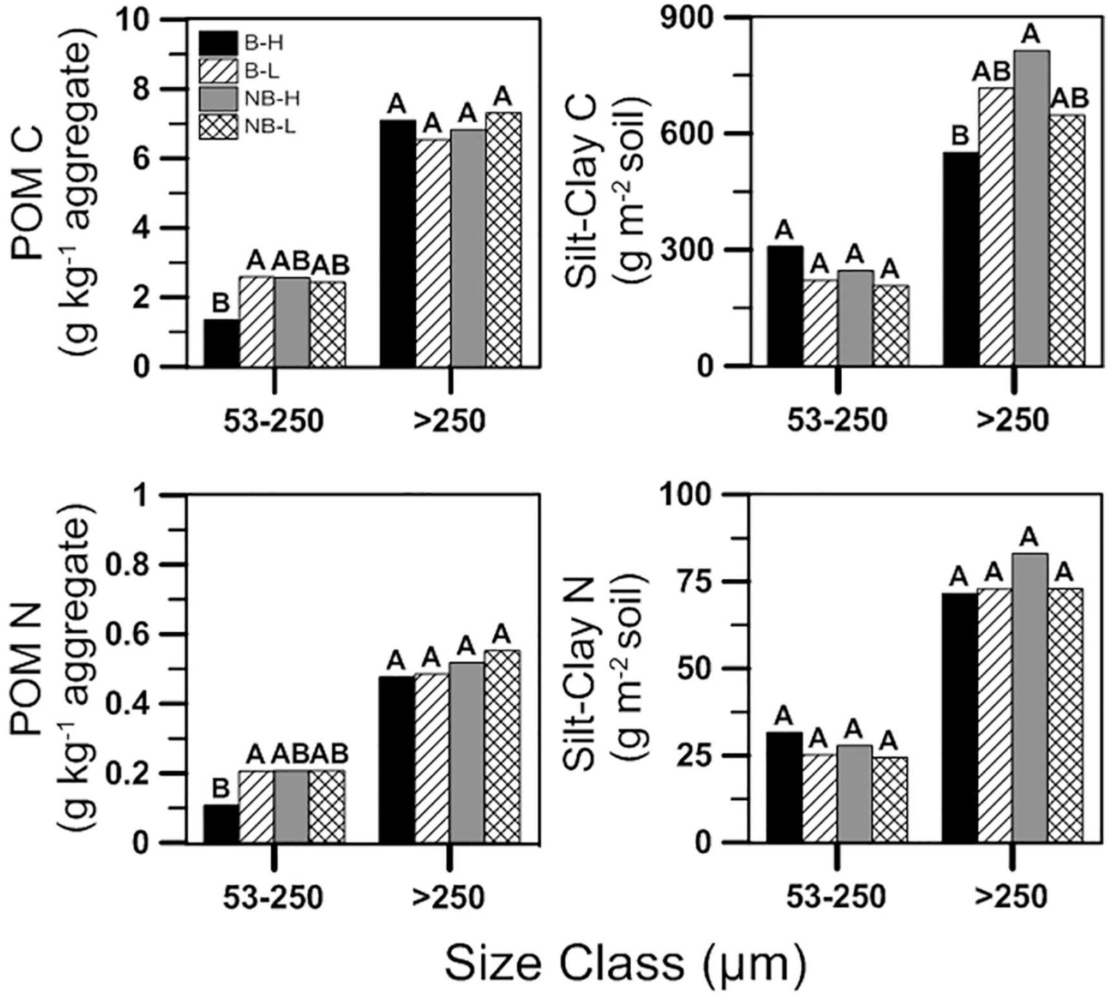

Fig. 6. Burn [burn (B) and no burn (NB)]-residue-level [high (H) and low (L)] treatment effects on particulate organic matter (POM) C (top-left), POM N (bottom-left) concentration, silt-clay-associated C (top-right) and silt-clay-associated N (bottom-right) contents among aggregate-size classes in the top 10 cm of soil in September 2015 following > 13 years of consistent management in a wheat-soybean, double-crop system near Marianna, AR. Different letters atop bars within a size class within a panel denote significant differences between treatment combinations.

not formally statistically compared, silt-clay C and N contents were consistently numerically greater in the coarse- than in the fine-associated fraction (Fig. 8). Averaged across irrigation and tillage treatments, the coarse-associated silt-clay C content was 1.5 times greater ($P < 0.01$) in the no-burn-high- ($814\ g\ m^{-2}$) than in the burn-high- ($551\ g\ m^{-2}$), whereas the coarse-associated silt-clay C content in the burn-low- ($716\ g\ m^{-2}$) and no-burn-low-residue combinations ($647\ g\ m^{-2}$) were intermediate and did not differ (Fig. 6). In contrast to C, coarse-associated silt-clay N content was unaffected ($P > 0.05$) by any field treatment and averaged $75.1\ g\ m^{-2}$ across all treatment combinations.

Averaged across irrigation and burn treatments, the fine-associated silt-clay C and N contents were 46 ($P < 0.01$) and 39% ($P < 0.01$) greater in the NT-high- (344 and $36.7\ g\ m^{-2}$, respectively) compared to the NT-low- (236 and $26.4\ g\ m^{-2}$, respectively), and 72% greater than the average of the CT-high- (209 and $22.9\ g\ m^{-2}$, respectively) and CT-low-residue combinations (192 and $23.2\ g\ m^{-2}$, respectively; Fig. 8). Furthermore, averaged across irrigation and residue-level treatments, the fine-associated silt-clay N content was 17% greater ($P = 0.01$) in the NT-burn ($34.0\ g\ m^{-2}$) compared to the NT-no-burn ($29.2\ g\ m^{-2}$) combination and 48% greater than in the burn and no-burn treatments under CT, which did not differ and averaged 23.0 and $23.1\ g\ m^{-2}$, respectfully (Fig. 9). In addition, averaged across burn, tillage, and residue-level treatments, the fine-associated silt-clay N content was 28.4% greater ($P < 0.05$) under the non-irrigated ($30.6\ g\ m^{-2}$) compared to the irrigated treatment ($23.9\ g\ m^{-2}$).

The coarse-associated silt-clay C:N ratios differed among several field treatments, however fine-associated silt-clay C:N ratios were unaffected by any field treatment. The coarse-associated silt-clay C:N ratio under the no-burn (C:N ratio = 9.6) was 12% greater ($P < 0.03$; Table 3) than in the burn treatment (C:N ratio = 8.6). The coarse-associated silt-clay C:N ratio was 22.1% greater ($P < 0.05$; Table 3) in the irrigated-low- (C:N ratio = 10.5) than in the irrigated-high-residue combination (C:N ratio = 8.2), while coarse-associated silt-clay C:N ratio in both residue levels under non-irrigated conditions did not differ and averaged 9.0. In contrast to the coarse-associated silt-clay fraction, the fine-associated silt-clay C:N ratio was unaffected ($P > 0.05$) by any field treatments and averaged 9.0 across all treatment combinations.

4. Discussion

Similar to the results from 2015 alone, from 2003 to 2014, annual post-harvest wheat residue masses in this long-term field study were significantly greater in the high- compared to the low-residue-level treatment in nine out of 11 years and numerically greater in 10 out of 11 years (Cordell et al., 2006; Norman et al., 2016; Verkler et al., 2008). Consequently, imposing differential N fertilization each year for the duration of this long-term study achieved the desired residue-level

Table 3
Analysis of variance (ANOVA) summary of the effects of tillage, residue level, burning, irrigation, and their interactions on coarse and fine particulate organic matter (POM) and silt-clay-associated carbon (C) and nitrogen (N) contents (g m^{-2} soil) and C:N ratios in the top 10 cm following > 13 years of consistent management in a wheat-soybean, double-crop production system at the University of Arkansas' Lon Mann Cotton Research Station near Marianna, AR on a silt-loam soil.

Source of variation	Coarse POM C	Coarse POM N	Fine POM C	Fine POM N	Coarse silt-clay C	Coarse silt-clay N	Coarse silt-clay C:N	Fine silt-clay C	Fine silt-clay N	Fine silt-clay C:N
	P									
Tillage (T)[a]	0.22	0.63	0.15	0.16	0.11	0.16	0.97	0.01	< 0.01	0.20
Residue level (RL)	0.54	0.29	0.14	0.04	1.00	0.42	0.40	0.01	< 0.01	0.13
Burn (B)	0.12	0.04	0.97	0.79	0.11	0.26	0.03	0.19	0.04	0.21
T × RL	0.79	0.45	0.85	0.84	0.85	0.61	0.24	< 0.01	< 0.01	0.43
T × B	0.98	0.80	0.98	0.68	0.33	0.74	0.81	0.12	0.01	0.74
B × RL	0.54	0.73	0.18	0.09	< 0.01	0.28	0.13	0.19	0.15	0.65
T × B × RL	0.64	0.92	0.58	0.50	0.16	0.06	0.93	0.63	0.26	0.59

Source of variation	Coarse POM C	Coarse POM N	Fine POM C	Fine POM N	Coarse silt-clay C	Coarse silt-clay N	Coarse silt-clay C:N	Fine silt-clay C	Fine silt-clay N	Fine silt-clay C:N
	P									
Tillage[a]	0.15	0.31	0.15	0.16	0.22	0.28	0.76	< 0.01	< 0.01	0.20
Residue level	0.59	0.23	0.05	0.01	0.93	0.47	0.37	< 0.01	< 0.01	0.23
Irrigation (I)	0.14	0.20	0.07	0.28	0.45	0.42	0.61	0.23	0.05	0.51
T × RL	0.66	0.42	0.82	0.83	0.80	0.62	0.42	< 0.01	< 0.01	0.39
T × I	0.34	0.22	0.26	0.15	0.19	0.07	0.92	0.68	0.83	0.42
I × RL	0.36	0.03	0.18	0.37	0.20	0.70	0.05	0.12	0.86	0.13
T × I × RL	0.23	0.25	0.64	0.75	0.85	0.89	0.37	0.82	0.27	0.13

[a] Two sets of three-factor ANOVAs were conducted due to the similar blocking structure for the burn and irrigation treatments.

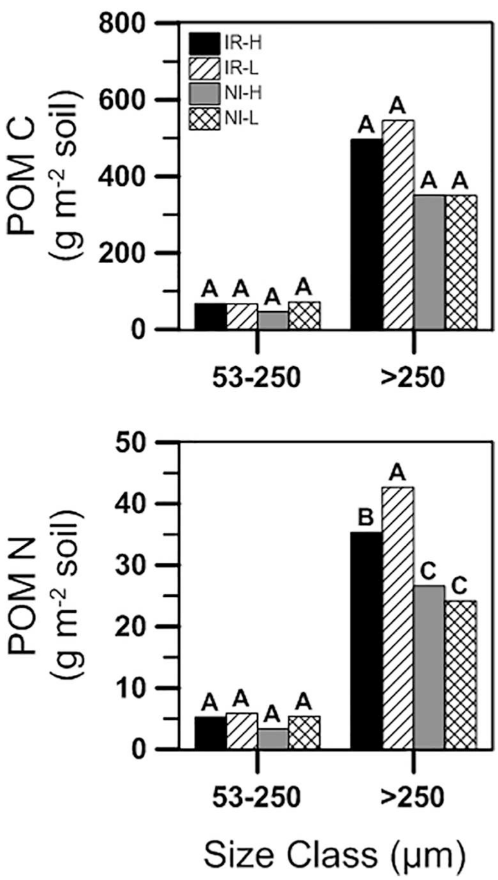

Fig. 7. Irrigation [irrigated (IR) and non-irrigated (NI)]-residue-level [high (H) and low (L)] treatment effects on particulate organic matter (POM) C (left) and N (bottom) contents among aggregate-size classes in the top 10 cm of soil in September 2015 following more than13 years of consistent management in a wheat-soybean, double-crop system near Marianna, AR. Different letters atop bars within a size class within a panel denote significant differences between treatment combinations.

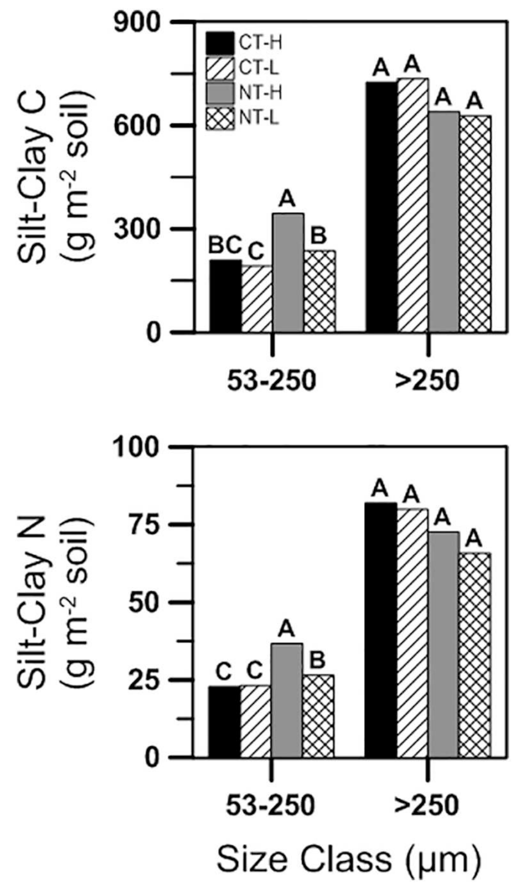

Fig. 8. Tillage [conventional tillage (CT) and no-tillage (NT)]-residue-level [high (H) and low (L)] treatment effects, averaged across irrigation and burn treatments, on silt-clay fraction C (top) and N (bottom) contents among aggregate-size classes in the top 10 cm of soil in September 2015 following more than13 years of consistent management in a wheat-soybean, double-crop system near Marianna, AR. Different letters atop bars within a size class within a panel denote significant differences between treatment combinations.

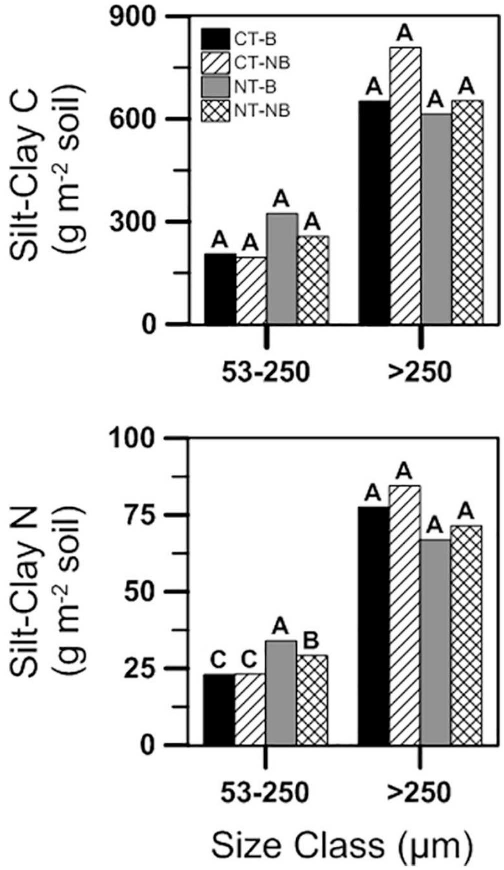

Fig. 9. Tillage [conventional tillage (CT) and no-tillage (NT)]-burn [burn (B) and no burn (NB)] treatment effects, averaged across irrigation and residue-level treatments, on silt-clay fraction C (top) and N (bottom) contents among aggregate-size classes in the top 10 cm of soil in September 2015 following more than13 years of consistent management in a wheat-soybean, double-crop system near Marianna, AR. Different letters atop bars within a size class within a panel denote significant differences between treatment combinations.

difference and that any subsequent effects of residue level after 13 years of consistent management were reasonably assumed to represent actual systematic and/or cumulative effects of residue-level differences. Furthermore, though some pH differences among field treatments existed, differences were relatively minor and agronomically insignificant, as soil pH in the top 10 cm in all plots were above the threshold soil pH of 5.5 to avoid soybean yield loss from a silt-loam soil (University of Arkansas Cooperative Extension Service (UACES), 2000).

4.1. Soil aggregation and associated C and N

Near-surface SOM and resulting structure have been shown to be negatively impacted from traditional management practices like CT (Franzluebbers and Doraiswamy, 2007; Lal and Bruce, 1999). The range of macro- and micro-aggregation reported in this study were similar to those reported by Tan et al. (2007) in the top 5 cm of a silt-loam soil (Aquultic Hapludalfs) under continuous corn (*Zea mays* L.) in Ohio and Carter et al. (2002) in the top 10 cm of 14 agricultural sites, including Gleysolic, Pedzolic, Luvisolic, and Brunisolic soils, in eastern Canada. However, contrary to that hypothesized and despite macro-aggregates generally being considered less resistant to microbial degradation (Six et al., 2004), soil macro-aggregation was greater under CT than NT in both residue-level treatments (Fig. 2). This result indicates that disking, as the common CT practice in the LMRD region, can promote the formation of larger soil aggregates (> 250 μm) by enhancing residue-to-soil contact from the physical transfer of fragments of organic material into the soil (Cotrufo et al., 2015). In addition, CT can increase the production of organic polymers from increased microbial activity following tillage, which has been associated with short-term increases in macro-aggregate proportions under CT compared to NT (Oorts et al., 2007).

In contrast to the results of this study, the macro-aggregate fraction was 37% greater under NT than CT in the top 5 cm of various silt-loam soils in a 15-yr wheat and sugar beet (*Beta vulgaris* L.) crop rotation study in Germany (Andruschkewitsch et al., 2013); however, tillage differences may have be accentuated from the shallower sampling depth than used in the present study. Blanco-Canqui et al. (2010) also reported an increase in the macro-aggregate fraction in the top 10 cm under irrigated NT management in an 8-yr crop rotation study on a Ulysses silt loam (Aridic Haplustoll) in Tribune, Kansas, where the substantially more arid environment in Kansas likely contributed to much lower SOM decomposition rates compared to much wetter eastern Arkansas environment. Frequent annual tillage compared to less frequent cultivation activities was show to reduce aggregation and aggregate-associated C and N storage after 23 years of management under various crop rotation on silt-loam soils in south-central Wisconsin (Cates et al., 2016). Similar to that hypothesized, macro-aggregation was reduced following the cumulative effects of residue burning compared to non-burning, which clearly demonstrates the negative effects that biomass and organic matter removal can have on soil aggregation when the return of fresh plant residues to the soil to promote microbial activity is restricted. Similarly, burning decreased glomalin, basidiomycetes population, and earthworm counts, which are all agents of soil aggregation, in the top 15 cm in a 7-year winter wheat-summer fallow field study on a silt loam (Typic Haploxeroll) in Oregon (Wuest et al., 2005).

In contrast to macro-aggregates, but similar to that hypothesized, soil micro-aggregation was reduced under CT than NT in both residue-level treatments, but collectively represented approximately one-third of the macro-aggregate proportion (Fig. 2). The tillage-induced reduction in micro-aggregate (53–250 μm) proportion by CT indicates less efficient microbial functioning at the smaller-aggregate scale because of less abundant SOM and SOC to promote aggregation due to greater oxidation under CT compared to NT (Smith et al., 2014a). This result also supports the concept of soil aggregate turn-over rate, whereby increased physical disruption of macro-aggregates by tillage reduces micro-aggregate retention by disrupting micro-aggregates prior to attaining long-term stability (Six et al., 2000). However, neither residue level nor burning impacted macro-aggregate or silt-clay fraction C and N contents (Figs. 4 and 5), while C and N contents in the micro-aggregate fraction collectively represented approximately one-third of the C and N, respectively, in the macro-aggregate and silt-clay fractions. These results indicate that, in the WSDC system studied on a loessial soil, the micro-aggregate fraction is either participating to a much lower degree in overall C and N cycling and storage or that the micro-aggregate fraction is more dynamic than the macro-aggregate and non-aggregated silt-clay fractions.

Though macro-aggregation was greater under CT than NT, the sand-free macro-aggregate C concentration was lower under CT than NT, demonstrating that the increased soil disturbance and SOM and SOC oxidation commonly associated with annual tillage (Smith et al., 2014a) can lead to a loss of macro-aggregate-protected C without negatively impacting the degree of macro-aggregation. Andruschkewitsch et al. (2013) reported greater macro-aggregate C under NT (20 g m^{-2}) compared to CT (13 g m^{-2}) in the top 5 cm of a silt-loam soil in Germany. Greater total water-stable aggregates and C and N contents, on average, have been reported under NT than CT across multiple rice (*Oryza sativa*)-containing rotations on a silt-loam soil in eastern Arkansas (Anders et al., 2012; Motschenbacher et al., 2013). In contrast to the results of this study, the macro-aggregate C concentration did not differ between NT and CT in the top 5 cm in a 26-yr-long winter-wheat/fallow study on a Duroc silt loam (Pachic Haplustoll) in Sidney,

Nebraska (Six et al., 1998). However, similar to the results of this study, Six et al. (1998) also reported a greater sand-free micro-aggregate C concentration in the top 5 cm under NT than CT in the same long-term field study.

Several treatment differences in the non-aggregated silt-clay proportion existed, but differences were relatively minor (Fig. 3). However, irrigation affected the non-aggregated silt-clay fraction, whereas the macro- and micro-aggregate fractions were unaffected by irrigation. Mechanistically, the furrow-irrigation scheme used in this study, which is also a widespread irrigation practice for many row crops in the LMRD region, could exacerbate the physical disintegration of unstable aggregates by slaking. However, the greater bulk-soil C contents under irrigated compared to dryland conditions in this study may have off-set the potential negative effects of slaking on soil aggregation, as the irrigated-high-residue and irrigated-CT combinations had the numerically lowest silt-clay proportion compared to their other respective treatment combinations (Fig. 3). Soil aggregation has also been reported to increase under high-residue conditions due to increased organic matter inputs and subsequent aggregate formation as residue decomposition occurs (Six et al., 2000).

4.2. C and N in particulate organic matter fractions

Residue burning had the largest impact on POM C and N. Burning plant residues at the soil surface can have varied effects on belowground processes. Aside from the loss of material from combustion to greatly reduce potential OM, C, and other nutrients from being returned to the soil, the removal of aboveground residues by burning impacts near-surface soil water dynamics. Verkler et al. (2008) demonstrated in this same long-term field study that soil water contents in the plow layer were consistently greater over the course of the soybean growing season following burning than non-burning. Greater soil moisture conditions are known to stimulate microbial activity, up to an optimal soil water content, thereby providing the opportunity for increased SOM decomposition and C loss due to oxidation and respiration under burning compared to non-burning, particularly in a high-residue situation achieved with fertilizer-N additions, where fine POM C and N concentrations were lowest among burn-residue-level combinations (Fig. 6). Furthermore, Cotrufo et al. (2015) demonstrated the interaction between microbial activity and dissolved organic matter, facilitated in the presence of greater soil water contents, is a significant pathway for SOM formation. Banger et al. (2010) reported a 26% increase in fine POM C concentration in the top 15 cm after treatment with 100 kg N ha^{-1} yr^{-1} (710 mg kg^{-1}) compared to an unamended control (565 mg kg^{-1}) after 16 year of consistent management in a rice-cowpea (*Vigna unguiculata*) cropping study in a sandy-loam Alfisol in India. Cropping systems that produce a large amount of aboveground biomass, coupled with reduced tillage frequency, can maintain both soil aggregation and POM-associated C and N due to the frequent availability of organic substrate for microbial activity (Cates et al., 2016).

Though coarse POM C concentration and content were unaffected by any field treatment evaluated in this study and CT, in general, did not have a substantial negative effect on C in the fine POM fraction, particulate organic C was shown to be lower under CT than minimal tillage in the top 20 cm after 10 years of annual cropping Alfisols in India (Prasad et al., 2016). However, Liebig et al. (2004) reported greater POM-fraction (i.e., 53–500 and 500–2000 μm) C content under minimum-tillage (585 and 139 g m^{-2}, respectively) than under NT (544 and 118 g m^{-2}, respectively) in the top 7.5 cm in an 8-yr-long crop rotation study on a Wilton silt loam (Pachic Haplustoll) in Mandan, North Dakota.

Generally, greater fine POM C and N under non-burning than burning also supported the contention that greater levels of organic matter returned to the soil as a result of non-burning can enhance POM N retention because of increased production of microbial- and plant-derived polysaccharides (Six et al., 2004), despite the lack of a burning effect on the fine or coarse POM C:N ratio. Surface residue removal, whether by burning, mowing and haying managed grasslands, or for biofuel feedstock, disrupts C and N storage and cycling in POM, which can negatively affect long-term soil sustainability to support optimal crop production (Ontl et al., 2015; Osborne et al., 2014). Though belowground C inputs have been shown to far exceed aboveground C inputs and eventual incorporation in various POM fractions due to greater humification rates (Mazzilli et al., 2015), it stands to reason that, when aboveground residue is removed, microbial activity can focus attention on the belowground biomass, which is already incorporated into the soil for easier physical access, thereby stimulating greater C losses than if a slow, yet steady, source of additional organic matter and C were available from aboveground materials.

In contrast to residue burning that affected fine POM, irrigation choice affected coarse POM, where coarse POM N content was lower under dryland than irrigated conditions between residue-level treatments (Fig. 7). A similar numeric trend occurred for coarse POM C content, but differences were not significant. The limited soil moisture associated with dryland production restricts not only plant growth, but other microbially mediated processes such as SOM decomposition. Consequently, there was less C and N released from fresh or raw plant material to be incorporated into the coarse POM fraction, which was corroborated by the documented greater bulk-soil C and N contents under irrigated compared to dryland conditions in this study after more than a decade of consistent management.

4.3. C and N in the silt-clay fraction

Though not formally statistically compared, similar to Six et al. (1998), silt-clay C and N contents were consistently numerically greater in the coarse than in the fine fraction (Figs. 6, 8, and 9). Both the coarse- and fine-associated silt-clay C and N contents were affected by numerous field treatments, but differences were generally small and were generally more numerous in the fine- and in the coarse-associated silt-clay fraction. Similar to coarse POM C and N, numerically smaller C and significantly smaller N contents occurred under CT than NT in the fine-associated silt-clay fraction (Fig. 9). Though Six et al. (1998) did not report a tillage effect on coarse- or fine-associated silt-clay-associated C and N concentrations in the top 5 cm, results of this study further highlight the potentially negative cumulative influence of CT on various soil aggregate and POM fractions and their associated C and N levels.

5. Conclusions

Though the results of this study were generated from a single soil sampling, results also represented the cumulative effects of nearly 14 complete cropping cycles in a WSDC production system with consistent management in a highly erodible loessial soil in the LMRD region of eastern Arkansas on soil aggregation, POM, and their C and N levels. The cumulative effects of the various combinations of traditional and alternative residue and water management practices (i.e., wheat-residue level, residue burning, tillage, and irrigation) in this long-term field study resulted in numerous differences among aggregate- and POM-related properties in the top 10 cm. Conventional tillage and residue burning had the most frequent impacts on soil aggregation, POM, and their C and N levels. In contrast to that hypothesized, results showed greater macro-aggregation under CT than NT, while, similar to that hypothesized, CT resulted in reduced micro-aggregation and less protected C in the micro-aggregate fraction under CT than NT. Though CT increases physical incorporation of residue, the increased residue-to-soil contact and the physical disruption of the soil can hinder micro-aggregate stability and stimulate C losses via oxidation and respiration. In contrast to the mixed results from CT, but similar to that hypothesized, long-term annual residue removal by burning not only substantially decreased the amount of organic material that can be

returned to the soil, but also reduced POM C and N, particularly in the fine fraction. However, contrary to that hypothesized, the cumulative effects of annual residue burning did not affect the degree of soil aggregation.

Though irrigated soybean production was hypothesized to have greater soil aggregation, POM, and aggregate- and POM-associated C and N due to greater above- and belowground plant biomass production compared to dryland production, results showed that neither the macro- nor micro-aggregate fractions in the top 10 cm were affected by irrigation. However, C and N retention in the coarse POM fraction tended to be favored by irrigation compared to dryland production as a result of greater biomass production from more optimal soil moisture conditions.

Despite being significant, many differences measured in this long-term field study were not large, which supports past inconsistencies reported in the literature, but demonstrate the complexity of interactions among soil aggregation, POM, and their C and N dynamics, particularly after annual implementation of soil- and residue-disturbing agricultural management practices for even longer than a decade, which field studies of shorter duration would fail to demonstrate. Though not large yet after 13 years, cumulative differences will likely continue to increase into the future and may affect the long-term sustainability of optimal crop production, particularly in the highly erodible loessial soils in the LMRD region.

Results of this long-term WSDC study have expanded the limited body of information on the dynamic interactions of various conventional and alternative management practice effects on soil aggregate and POM fractions. Results showed that conventional tillage and burning do not always significantly reduce soil C, greater surface residue does not always significantly increase soil C, and irrigation and N fertilization, which increase biomass production, can at least numerically increase soil C. Results also showed that alternative management practices, such as NT and non-burning, that increased aggregate-, POM-, and silt-clay-associated C and N storage, can contribute to improved soil health and long-term sustainability. Mitigation of climate-change-related greenhouse gas concentrations in the atmosphere can be realized by reducing SOM oxidation, microbial respiration, and CO_2 emissions.

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References

Álvaro-Fuentes, J., López, M.V., Cantero-Martinez, C., Arrúe, J.L., 2008. Tillage effects on soil organic carbon fractions in Mediterranean dryland agroecosystems. Soil Sci. Soc. Am. J. 72, 541–547.

Amuri, N., Brye, K.R., Gbur, E.E., Popp, J., Chen, P., 2008. Soil property and soybean yield trends in response to alternative wheat residue management practices in a wheat-soybean, double-crop production system in eastern Arkansas. J. Integr. Biosci. 6, 64–86.

Anders, M.M., Brye, K.R., Olk, D.C., Schmid, B.T., 2012. Rice rotation and tillage effects on soil aggregation and aggregate carbon and nitrogen dynamics. Soil Sci. Soc. Am. J. 76, 994–1004.

Andruschkewitsch, R., Geisseler, D., Koch, H.J., Ludwig, B., 2013. Effects of tillage on contents of organic carbon, nitrogen, water-stable aggregate and light fraction for four different long-term trials. Geoderma 192, 368–377.

Balesdent, J., Chenu, C., Balabane, M., 2000. Relationship of soil organic matter dynamics to physical protection and tillage. Soil Tillage Res. 53, 215–230.

Banger, K., Kukal, S.S., Toor, G., Sudhir, K., Hanumanthraju, T.H., 2009. Impact of long-term additions of chemical fertilizers and farm yard manure on carbon and nitrogen sequestration under rice-cowpea cropping system in semi-arid tropics. Plant Soil 318, 27–35.

Banger, K., Toor, G.S., Biswas, A., Sidhu, S.S., Sudhir, K., 2010. Soil organic carbon fractions after 16-years of applications of fertilizers and organic manure in a Typic Rhodalfs in semi-arid tropics. Nutr. Cycl. Agroecosyst. 86, 391–399.

Blanco-Canqui, H., Klocke, N., Schlegel, A., Stone, L., Rice, C., 2010. Impacts of deficit irrigation on carbon sequestration and soil physical properties under no-till. Soil Sci. Soc. Am. J. 74, 1301–1309.

Brye, K.R., 2012. Long-term effects of aboveground biomass removal by burning on potential nutrient recycling. Crop Manag. https://doi.org/10.1094/CM-2012-0822-01-RS.

Brye, K.R., Pirani, A.L., 2005. Native soil quality and the effects of tillage in the Grand Prairie region of eastern Arkansas. Am. Midl. Nat. 154, 28–41.

Brye, K.R., Cordell, M.L., Longer, D.E., Gbur, E.E., 2006a. Residue management practice effects on soil surface properties in a young wheat-soybean double-crop system. J. Sustain. Agric. 29, 121–150.

Brye, K.R., Longer, D.E., Gbur, E.E., 2006b. Impact of tillage and residue burning on carbon dioxide flux in a wheat-soybean production system. Soil Sci. Soc. Am. J. 70, 1145–1154.

Carter, M.R., Angers, D.A., Gregorich, E.G., Bolinder, M.A., 2002. Characterizing organic matter retention for surface soils in eastern Canada using density and particle size fractions. Can. J. Soil Sci. 83, 11–23.

Cates, A.M., Ruary, M.D., Hedtcke, J.L., Posner, J.L., 2016. Long-term tillage, rotation and perennialization effects on particulate and aggregate soil organic matter. Soil Tillage Res. 155, 371–380.

Churchman, G., Tate, K., 1986. Effect of slaughterhouse effluent and water irrigation upon aggregation in seasonally dry New Zealand soil under pasture. Soil Res. 24, 505–516.

Cordell, M.L., Brye, K.R., Longer, D.E., Gbur, E.E., 2006. Residue management practice effects on soybean establishment and growth in a young wheat-soybean double-cropping system. J. Sustain. Agric. 29, 97–120.

Cotrufo, M.F., Soong, J.L., Horton, A.J., Campbell, E.E., Haddix, M.L., Wall, D.H., Parton, W.J., 2015. Formation of soil organic matter via biochemical and physical pathways of litter mass loss. Nat. Geosci. 8, 776–779.

Delong, R.E., Slaton, N.A., Brye, K.R., Wolf, N., Mozaffari, M., 2003. Relationships between organic carbon and other chemical properties in Arkansas soils. In: Agronomy Abstracts. ASA, Annual Meeting, Denver, CO.

Desrochers, J., 2017. Agronomic Management Practice Effects on Particulate Organic Matter and Infiltration in a Wheat-soybean, Double-crop System in Eastern Arkansas (MS Thesis). Univ. of Arkansas, Fayetteville.

Elliott, E.T., Palm, C.A., Reuss, D.E., Monz, C.A., 1991. Organic matter contained in soil aggregates from a tropical chronosequence: correction for sand and light fraction. Agric. Ecosyst. Environ. 34, 443–451.

Environmental Protection Agency (EPA), 2016. Inventory of U.S. Greenhouse Gas Emissions and Sinks. EPA, Washington, D.C, pp. 1990–2010.

Franzluebbers, A.J., Doraiswamy, P.C., 2007. Carbon sequestration and land degradation. In: Sivakumar, M.V.K. (Ed.), Climate and Land Degradation. Springer Verlag, New York, pp. 339–354.

Garland, G., Bünemann, E.K., Six, J., 2016. New methodology for soil aggregate fraction to investigate phosphorus transformations in iron oxide-rich tropical agricultural soil. Eur. J. Soil Sci. 68, 115–125.

Gosling, P., Parson, N., Bending, G.D., 2013. What are the primary factors controlling the light fraction and particulate soil organic matter content of agricultural soils. Biol. Fertil. Soils 49, 1001–1014.

Intergovernmental Panel on Climate Change (IPCC), 2013. The physical science basis. In: Contribution of Working Group I to the Fifth Assessment Report of the intergovernmental Panel on Climate Change, Available at. http://www.climatechange2013.org/images/report/WG1AR5_ALL_FINAL.pdf (verified 17 Aug. 2017).

Jacobs, A., Brye, K.R., King, R., Douglass, J., Wood, L.S., Purcell, L.C., Looper, M., 2015. Switchgrass management practice effects on near-surface soil properties in west-central Arkansas. Open J. Soil Sci. 5, 69–86.

Jagadamma, S., Lal, R., 2010. Distribution of organic carbon in physical fractions of soils as affected by agricultural management. Biol. Fertil. Soils 46, 543–554.

Lal, R., 2000. World cropland soils as a source or sink for atmospheric carbon. Adv. Agron. 71, 145–191.

Lal, R., Bruce, J.P., 1999. The potential of world cropland soils to sequester C and mitigate the greenhouse effect. Environ. Sci. Pol. 2, 77–185.

Liebig, M.A., Tanaka, D.L., Wienhold, B.J., 2004. Tillage and cropping effects on soil quality indicators in the northern Great Plains. Soil Tillage Res. 78, 131–141.

Malhi, S.S., Gill, K.S., 2002. Fertilizer N and P effects on root mass of brome grass, alfalfa and barley. J. Sustain. Agric. 19, 51–63.

Marschner, P., Umar, S., Baumann, K., 2011. The microbial community composition changes rapidly in the early stages of decomposition of wheat residue. Soil Biol. Biochem. 43, 445–451.

Mazzilli, S.R., Kemanian, A.R., Ernst, O.R., Jackson, R.B., Pineiro, G., 2015. Greater humification of belowground than aboveground biomass carbon into particulate soil organic matter in no-till corn and soybean crops. Soil Biol. Biochem. 85, 22–30.

Motschenbacher, J.M., Brye, K.R., Anders, M.M., Gbur, E.E., Slaton, N.A., Evans-White, M.A., 2013. Rice rotation and tillage effects on water-stable soil macroaggregates and their associated carbon and nitrogen contents in a silt-loam soil. Soil Sci. 178, 596–611.

National Oceanic and Atmospheric Administration (NOAA), 2017a. Global summary of the monthly station details. Available at. https://www.ncdc.noaa.gov/cdo-web/datasets/GSOM/stations/GHCND:USC00034638/detail (verified 11 Sept. 2017).

National Oceanic and Atmospheric Administration (NOAA), 2017b. Data Tools: 1981–2010 Normals. Available at. https://www.ncdc.noaa.gov/cdo-web/datatools/normals (verified 17 Aug. 2017).

Natural Resources Conservation Service (NRCS), 2006. Land resource regions and major land resource areas of the United States, the Caribbean, and the Pacific Basin. vol. 296 DC, Washington.

Natural Resources Conservation Service (NRCS), Soil Survey Staff (SSS), 2017. Web soil survey: Soil data mart. https://websoilsurvey.sc.egov.usda.gov/ (verified 17 Aug.

2017).
Norman, C.R., Brye, K.R., Gbur, E.E., Chen, P., Rupe, J., 2016. Long-term management effects on soil properties and yields in a wheat-soybean, double-crop system in eastern Arkansas. Soil Sci. 181, 1–12.
Ontl, T.A., Cambardella, C.A., Schulte, L.A., Kolka, R.K., 2015. Factors influencing soil aggregation and particulate organic matter resppnses to bioenergy crops across a topographic gradient. Geoderma 255-256, 1–11.
Oorts, K., Bossuyt, H., Labreuche, J., Merckx, R., Nicolardot, B., 2007. Carbon and nitrogen stocks in relation to organic matter fractions, aggregation and pore size distribution in no-tillage and conventional tillage in northern France. Eur. J. Soil Sci. 58, 248–259.
Osborne, S.L., Johnson, J.M.F., Jin, V.L., Hammerbeck, A.L., Varvel, G.E., Schumacher, T.E., 2014. The impact of corn residue removal on soil aggregates and particulate organic matter. Bioenergy Res. 7, 559–567.
Paul, E.A., 2016. The nature and dynamics of soil organic matter: plant inputs, microbial transformations, and organic matter stabilization. Soil Biol. Biochem. 98, 109–126.
Prasad, J.V.N.S., Rao, Ch.S., Srinivas, K., Jyothi, Ch.N., Venkateswarlu, B., Ramachandrappa, B.K., Dhanapal, G.N., Rivichandra, K., Mishra, P.K., 2016. Effect of ten years of reduced tillage and recycling of organic matter on crop yields, soil organic carbon and its fractions in Alfisols of semi arid tropics of southern India. Soil Tillage Res. 156, 131–139.
Pretty, J., 2008. Agricultural sustainability: concepts, principles and evidence. Philos. Trans. R. Soc. Lond. Ser. B Biol. Sci. 363, 447–465.
Puget, P., Chenu, C., Balesdent, J., 1995. Total and young organic matter distribution in aggregates of silty cultivated soils. Eur. J. Soil Sci. 46, 449–459.
Rasmussen, P.E., Parton, W.J., 1994. Long-term effects of residue management in wheat-fallow: I. Inputs, yields and soil organic matter. Soil Sci. Soc. Am. J. 58, 523–530.
Sanford, J.O., 1982. Straw and tillage management practices in soybean-wheat double-cropping. Agron. J. 74, 1032–1035.
Six, J., Elliott, E.T., Paustian, K., Doran, J.W., 1998. Aggregate and soil organic matter accumulation in cultivated and native grassland soils. Soil Sci. Soc. Am. J. 62, 1367–1377.
Six, J., Elliott, E.T., Paustian, K., 1999. Aggregate and soil organic matter dynamics under conventional and no-tillage systems. Soil Sci. Soc. Am. J. 63, 1350–1358.
Six, J., Elliott, E.T., Paustian, K., 2000. Soil macroaggregate turnover and microaggregate formation: a mechanism for C sequestration under no-tillage agriculture. Soil Biol. Biochem. 32, 2099–2103.
Six, J., Bossuyt, H., Degryze, S., Denef, K., 2004. A history of research on the link between (micro)aggregates, soil biota, and soil organic matter dynamics. Soil Tillage Res. 79, 7–31.
Six, J., Elliott, E.T., Paustian, K., 2014. Aggregate-associated soil organic matter as an ecosystem property and a measurement tool. Soil Biol. Biochem. 68, A4–A9.
Smith, S.F., Brye, K.R., Gbur, E.E., Chen, P., Korth, K., 2014a. Long-term residue management effects on soil respiration in a wheat-soybean, double-crop system. Soil Sci. 179, 118–129.
Smith, S.F., Brye, K.R., Gbur, E.E., Chen, P., Korth, K., 2014b. Residue and water management effects on aggregate stability and aggregate-associated carbon and nitrogen in a wheat-soybean, double-crop system. Soil Sci. Soc. Am. J. 78, 1378–1391.
Stevenson, F.J., 1986. Carbon Balance of the Soil and Role of Organic Matter in Soil Fertility. John Wiley and Sons, New York, NY.
Tan, Z., Lal, R., Owens, L., Izaurralde, R.C., 2007. Distribution of light and heavy fractions of soil organic carbon as related to land use and tillage practice. Soil Tillage Res. 92, 53–59.
United States Department of Agriculture (USDA), National Agricultural Statistics Service (NASS), 2017. Statistics by state: Arkansas. https://quickstats.nass.usda.gov (verified 25 September 2017).
University of Arkansas Cooperative Extension Service (UACES), 2000. Arkansas Soybean Handbook. Misc. Publ. 197. Coop. Ext. Serv., Univ. of Arkansas, Little Rock, AR.
Verkler, T.L., Brye, K.R., Gbur, E.E., Popp, J.H., Amuri, N., 2008. Residue management and water delivery effects on season-long surface soil water dynamics in soybean. Soil Sci. 173, 444–455.
Verkler, T.L., Brye, K.R., Popp, J.H., Gbur, E.E., Chen, P., Amuri, N., 2009. Soil properties, soybean response, and economic return as affected by residue and water management practices. J. Sustain. Agric. 33, 716–744.
Wander, M., Bidart, M., 2000. Tillage practice influences on the physical protection, bioavailability and composition of particulate organic matter. Biol. Fertil. Soils 32, 360–567.
Wuest, S.B., Caesar-TonThat, T., Wright, S.F., Wiliams, J.D., 2005. Organic matter addition, N, and residue burning effects on infiltration, biological, and physical properties of an intensively tilled silt-loam soil. Soil Tillage Res. 84, 154–167.
Yoo, G., Wander, M.M., 2008. Tillage effects on aggregate turnover and sequestration of particulate and humified soil organic carbon. Soil Sci. Soc. Am. J. 72, 670–676.